THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IV REFRIGERATING TECHNIQUE, INTERNAL COMBUSTION ENGINES,
BOILERS AND TURBINES,2015, ISSN 1221-4558

A REVIEW OF RECENT RESEARCH ON SAND DUNES FORMATION

Eugen DIMOFTE, Florin POPESCU, Ion V. ION
”Dunarea de Jos” University of Galati

ABSTRACT: This work aims at analysing the current stadium of research on building-up of the sand dunes and at being the starting point for a much detailed analysis on the topic. Throughout this essay practical studies are presented on the erosion, migration and building-up of sand dunes in the Sahara Desert; studies based on on-field measurements. Then there’s a presentation of an experimental study on sand dunes erosion performed in the aero-dynamic tunnel; a study to determine the friction speeds on each of the three models used. The practical studies are followed by a numeric modelling study whose results are close enough to the experimental results so as to be validated. The one before last chapter describes methods and techniques of stabilizing and anchoring sand dunes, their modality of putting them into practice, as well as the way in which numeric modelling can be used in the study of mechanically anchoring and biologically stabilizing sand dunes.

KEYWORDS: sand dunes, erosion, deflation, wind tunnel, numerical modelling

1. INTRODUCTION

According to the United Nation Convention to Combat Desertification (UNCCD), desertification is defined as being “the degradation of soil in the arid, semiarid and dry areas, as a result of the action of different factors, including climatic changes, and of human activities”.

The purpose of this paper is to carry out an analysis of recent research on sand dunes formation and migration, setting the basis for a future work on a numerical model to be used in the analysis and prediction of desertification. Relevant are the reviews performed by Livingstone et al. [1] on the geomorphological and numerical studies of the formation of sand dunes and those of Durán et al. [2], on research to find a model capable of simulating the evolution of dunes.

This paper contains five chapters and conclusions and analyses the phenomena both via experimental studies as well as via those performed in the experimental aero-dynamic tunnel. Another important aspect is represented by the study of using numerical modelling within these researches and how they manage to offer results comparable with those of the experimental study.

1. FIELD STUDY ON SAND DUNE EROSION, MIGRATION, AND FORMATION

The field studies presented were carried out in the Sahara Desert and are aimed at investigating the processes of sand dunes erosion, migration, initiation and their interaction. Such research requires long periods of field study to capture the processes involved in sand dunes initiation and nucleation. Field research of dune formation is fundamental as it cannot be reproduced under controlled laboratory conditions without changing the density of the working fluid [3].

Dunes can arise spontaneously by evolving from proto-dunes [4]. The formation of small barchans from proto-dunes comprises five phases. In the initial phase, sand patches of a few cm high are generated. In the second phase, these sand patches are exposed to aeolian waves of sand, which lead to their growth. The accumulation of sand continues, so that during the third phase, these patches become 25 to 40 cm thick, leading to the formation of proto-dunes with a grain slip on their lee slopes. During the fourth phase, a small dune of 1 to 1.5 m height with a grain flow on the lee side appears. The last phase is the formation of a crescent-shaped barchan 1 to 2 m high [5].

Dune movement process is affected by various sand transport processes, especially at the dune crest [6]. After many field measurements it was concluded that the sand transport flux over the dune crest can be expressed as an exponential function and a Gaussian function. A correlation coefficient analysis of the complex relationship between the sand transport and wind conditions (mean velocity, maximum wind velocity, shear velocity, potential sand transport, and wind direction) and the surface properties (roughness length, fetch length) indicated that the sand transport rate over the dune crest is positively correlated with the mean velocity and shear velocity and is negatively correlated with the wind direction [7].

Measurements performed in the Badain Jaran Desert in western China demonstrated that in addition to average wind parameters, dune height is highly sensitive to local geology, subsurface characteristics, and topography, and interactions between changing climate conditions and aeolian and fluvial processes.

The simulation and interpretation of dunes should take into consideration these additional factors.

1.1. WORKING METHODOLOGY

A relevant field study of the erosion, migration and initiation of sand dunes was performed by Hicham [8] in the Sahara Desert. The dune contours were measured with hand-held, 5 m-spaced GPS receivers. The shape of the slip face was recorded in photographs taken from the ground level.

The technique of stakes was used to obtain the dune profiles. Thus, two lines of stakes were installed on the windward side, with the first line parallel to the direction of the prevailing winds and the second perpendicular to the first one. After installation of stakes, the distance between stakes along the profile was measured with an accuracy of 5 mm and the angle with an accuracy of 0.1°. These sets of measurements were combined in the following equation:

$$\delta h = \frac{p}{\sqrt{1+p^2}}\delta s \qquad (1)$$

where: p is the slope angle, δh is the height variation and δs is the distance between two consecutive stakes.

Once the profiles were obtained, the accumulation or the erosion at each post was recorded, the percentage evolution of the profile being then analysed by the same Hicham and Douday [9]. Two methods have been used for the measurement of patch wavelength. The first consists in using a tape measure for direct measurements and ensures an accuracy of 5 cm. The second is based on aerial photographs allowing (0.2 – 1) m accuracy [9].

Figure 1 shows the transformation of a proto-dune (Fig. 1.a.) with an initial length of 15 m into a small barchan dune during a period of five days. The longitudinal profile of this dune (Fig. 1.c.) recorded on the 9th day shows that the maximum thickness of the dune is 30 cm. A comparison between this profile and a second one recorded two days after shows the erosion of the windward slope and the accumulation of sand around the ridge, as illustrated in Fig. 1.d. Figure 1.e. shows the wind rose for the period in the studied area [8].

Either erosion or accumulation can occur, depending on the increase or decrease of the maximum sand flow. Furthermore, the increase or decrease of the crest depends on the relative position of maximum sand flow. There is a saturation length which is proportional to the turbulent drag length [10]:

$$L_{sat} \approx 4.4\frac{\rho_s}{\rho_f}d \qquad (2)$$

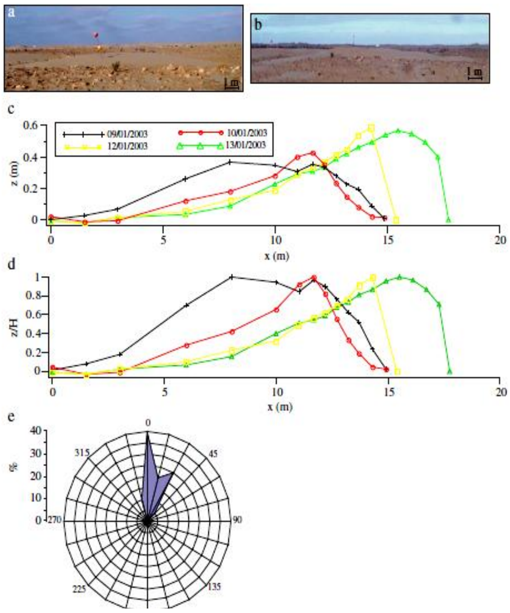


Fig. 1. a) Small sand agglomeration; b) semilunar dune of elementary dimensions; c) and d) longitudinal profile showing the transformation of the sand agglomeration into a dune; e) the wind rose for the studied area [8].

where: ρ_s is the sand density, ρ_f is the density of the fluid and d is the sand grain diameter. Experimental measurements indicated the saturation length within the studied area to be L_{sat} =1.7 m [8].

There is a minimal wavelength at which the formation of dunes starts $\lambda_N \approx 7\ L_{sat}$. Sand accumulations with a wavelength larger than λ_N will lead to the formation of sand dunes, whereas those with a wavelength equal or smaller than λ_N will be eroded and will disappear [8].

Other studies have shown that there are other conditions which could initiate the process of barchan formation. One of these is represented by the existence of topographic barriers which may act as genuine stoppers, reducing the wind velocity and leading to big sand pile or cliff top dune being created. Another condition is the existence of small barchans in interaction which form, by collision, one big barchan. Numerical modelling used for studying dune size and position has shown that the variation in wind direction and the neighbouring effect play a decisive part in the formation of megabarchan by the remote interaction between barchans.

2. WIND TUNNEL STUDY OF SAND DUNES EROSION

Friction velocity is a very important parameter for the understanding of aeolian and soil erosion phenomena. It is defined as the minimum friction velocity required for the aerodynamic forces to exceed the wind erosion. To study this parameter, Faria et al. [11] have performed both numerical modelling and experimental study in a wind tunnel, as well as through field research.

Soil erosion depends on factors such as soil humidity, biological crusts covering the ground, quantity and distribution of vegetation, surface roughness, but also on the presence of non-erodible elements [12]. To determine the influence of the sand dune slope angle on the friction velocity, three models were studied, basically shaped transverse dunes with the windward slopes of 10°, 20° and 32°. All three models had the crest height H = 75 mm, and the angle of the leeward slopes equal to the angle of repose of 32° [12]. Two series of tests have been performed. The first series targeted the measurement of threshold friction velocity distribution across the windward slope. During the second series of experiments the erosion over the longitudinal profiles of three models of triangular shape at specific time intervals was recorded.

The physical models were placed on the floor of the working chamber inside the wind tunnel, equally spaced from its sidewalls (Fig. 2).

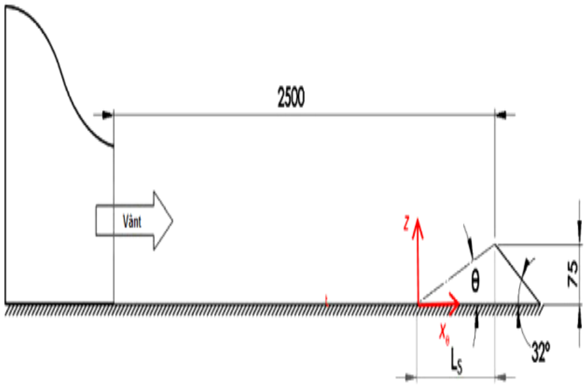


Fig. 2. Schematic diagram of the testing area of wind tunnel and the location of model (sizes in mm) [11].

The average velocity profile of the airflow, measured at the half-width of the empty settling chamber and at 2.4 m from the nozzle exit is given by the following equation:

$$\frac{u}{U_0}\left(\frac{z}{\delta}\right)^{\alpha} \tag{3}$$

where u (m/s) is the longitudinal wind velocity component, U_0 (m/s) is the reference wind velocity, and z (m) is the vertical height measured from the ground.

According to the given conditions, the boundary layer thickness is δ = 0.1 m and the constant α is equal to 0.11. Several wind velocities were used, namely 8.3; 9.1; 9.9 and 10.7 m/s, which led to four different velocity profiles, as illustrated in Fig. 3 [11].

The piles of triangular shape were tested for different windward slope angles, namely 10^o, 20^o, and 32^o, the models being named S10, S20, and respectively S32. The height of all models is 75 mm while, according to analysis, the prevailing particles have a diameter of approximately 0.5 mm.

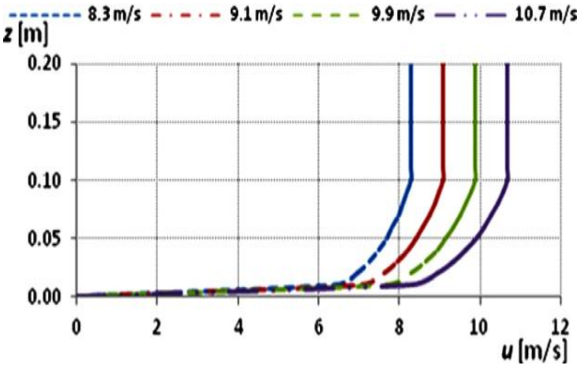


Fig. 3. Incident velocity profile for various undisturbed wind velocities tested [11].

In order to analyse the influence of wind erosion on the evolution of sand pile shape, a series of erosion tests have been performed by laser measurements. The sand model was exposed to the intended wind velocity for certain time periods t = 1; 2; 3; 5; 7; 10; 15 and 20 minutes. Measurements of the wall shear stress or friction velocity along the slope of different piles and pressure have been recorded (Fig. 4). It can be noted that he friction velocity increases proportionally to the undisturbed wind speed, which indicates that the entrainment of particles is enhanced at higher wind speeds and the friction velocity increases along the stoss surface [11].

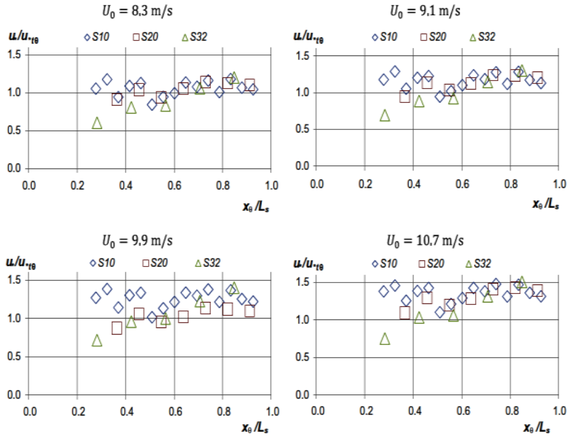


Fig. 4. Experimental distribution of the friction velocity along the three slopes, for different wind velocities [11].

3. NUMERICAL MODELLING OF SAND DUNES EROSION

Experimental studies and field observations provide information which is valid qualitatively to describe processes and from a quantitative point of view, only for the studied cases. The results obtained by these methods cannot be used to simulate the evolution of erosion and dune migration in other real cases.

The numerical modelling was performed in Ansys CFX, the discretization grid was generated using CFX Mesh and CFX Solver was used to solve the proposed cases [11]. The computational domain is assumed to be two-dimensional, involving symmetry conditions (Fig. 6).

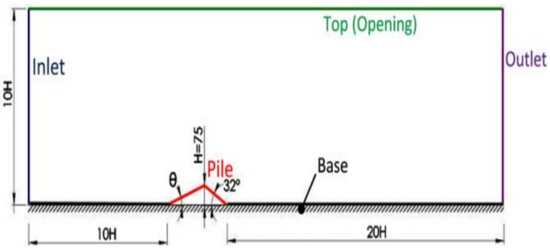


Fig. 6. The computational domain [11].

A series of numerical simulations were performed for multiple values of sand-grain roughness *k*. Good results compared to experimental values being obtained for *k* = d/30. The benchmark tests performed for the model S32 are presented in Fig. 7, which shows the predicted values and the wind tunnel results. it can be noted that the sand grain roughness has some influence on the numerical predictions, especially in the region $x_h/L_s > 0.5$ [11].

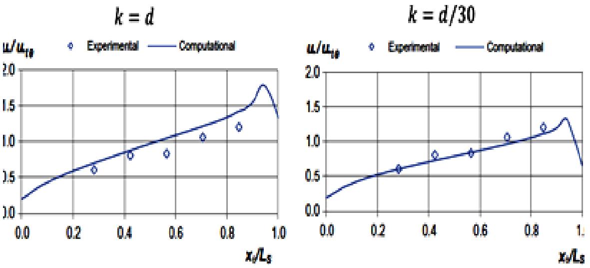


Fig. 7. The influence of roughness (*k*) on the distribution of friction velocity for the S32 model at a wind velocity U_0 = 8.3 m/s [11].

The numerical model is validated by comparing the experimental data for the friction velocity with the results obtained through numerical simulation. Figure 8 illustrates the comparison between the experimental and numerical results of the friction velocity distribution along the windward slope for the S20 model and considering different wind velocities. It can be noticed that the absolute maximum deviation for the S20 model is situated between 12.7% and 13.8%, while the average one varies from 5.3% to 6.5% for the different wind velocities tested. Similar results were obtained for different models [11]. Figure 8 clearly shows that the numerical model accurately predicts the friction velocity distribution and can be successfully used for future cases in order to predict the shape variation dynamics of the sand dunes.

The shape at different time steps of the three eroded models and the evolution of the friction velocity obtained through numerical methods can be observed in the diagrams in Fig. 9. The agreement between numerical and experimental results is better for low wind speeds, regardless of the windward slope angle. This is due to the actual limits of Ansys CFX and Ansys Fluent in modelling accurately this kind of multiphasic flow being a problem which can be improved. However, a lower wind velocity means, in fact, less erosion, hence an inferior rate of variation of the windward slope angle. For a given wind velocity, an increase in the angle of the windward slope causes the area exposed to erosion to approach the crest, which leads to a decrease of eroded surface [11].

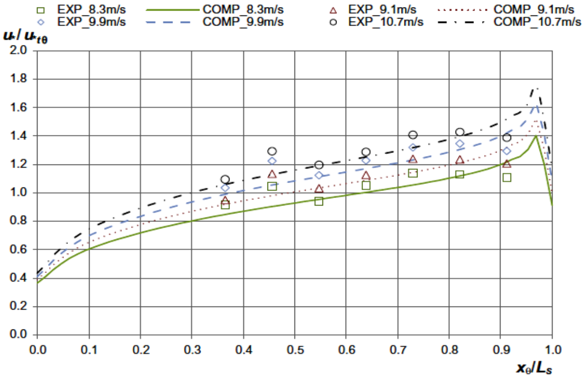


Fig. 8. Comparison between experimental and numerical results of friction velocity distribution at different wind velocities for S20 [11].

The results of numerical modelling indicate the existence of a large area of recirculation for all models, as shown in Fig. 9. The friction velocity within the recirculation bubble is quite low, leading to almost null local aeolian erosion (Ferreira and Oliveira 2009). It was noticed that the location of reattachment point is independent of the wind velocity. This observation is valid for numerical simulations that take into account only wind velocities situated within the limits of transient flow regime. Thus, only the results for a wind velocity U_0 = 8.3 m/s are presented in Fig. 9 [11].

The study confirmed the experimental results from [12], where the length of the recirculation zone increases with the windward slope. For all the piles the flow separation occurs at the pile crest. It was observed that the location of the reattachment point did not change with the undisturbed velocity (Fig. 10).

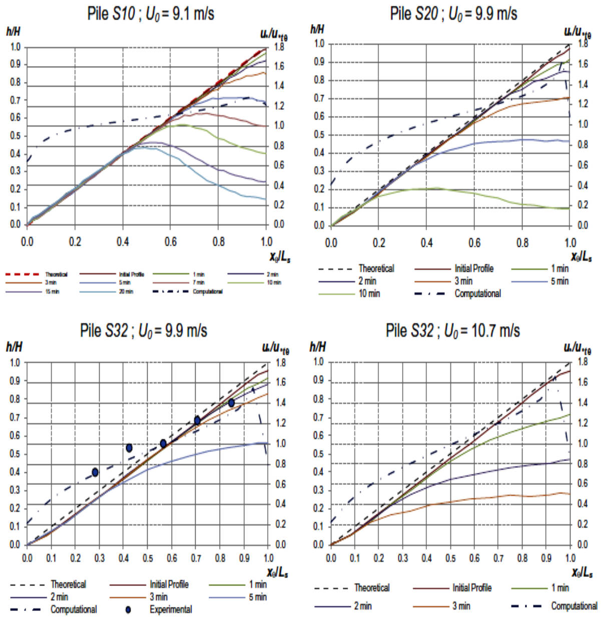


Fig. 9. Very good agreement between experimental and numerical results in the determination of friction velocity and the contours of models [11].

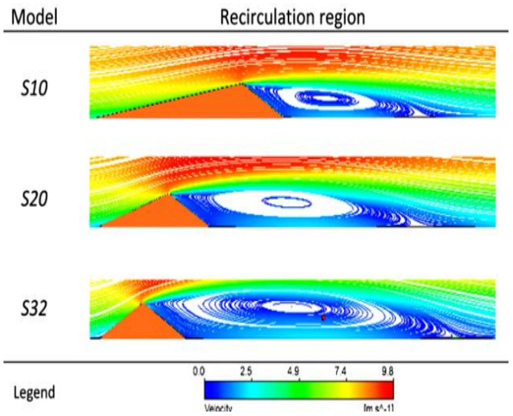


Fig. 10. Determination of recirculation areas on the leeward slopes for the three models at a wind velocity U_0 = 8.3 m/s [11].

In recent studies of Burkow and Griebel [16] the mathematical model of the flow is given by the Navier Stokes equations but an additional model is used, capable of reproducing the geomorphological features resulting from the fluid flow. Both models are coupled into a 3D final model which allows numerical simulation of sand dune erosion and dispersion.

A code (NaSt3DGPF), which is under steady development, was created for numerical simulations [17], NaSt3DGPF uses the k-ε turbulence model and a Smagorinski subgrid scale model [18]. The code is written in C/C++ and is employing domain decomposition methods [19].

The Navier-Stokes equations for a 3D single phase flow are given by the following equation:

$$\frac{\partial u_i}{\partial t} + \sum_{k=1}^{3} u_k \frac{\partial u_i}{\partial x_k} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\sum_{k=1}^{3} \frac{\partial^2 u_i}{\partial x_k \partial x_k} + \frac{1}{Fr} g_i \qquad (4)$$

$$\sum_{k=1}^{3} u_k \frac{\partial u_k}{\partial x_k} = 0$$

where: u is the velocity, g is the gravitational force, Re is the Reynolds number, Fr the Froude number.

NaSt3DGPF was coupled with Exner model, which arises from the principle of conservation of mass [20]. It states that the height h of the sediment surface changes according to the incoming and outgoing mass rates and is given by the equation [22]:

$$\frac{\partial h}{\partial t} = -\sum_{k-1}^{2} \frac{\partial q_k(\tau(u))}{\partial x_k} \qquad (5)$$

where q is mass rate, $\tau(u)$ is the shear stress and u is the fluid velocity.

This model shows the morphological evolution of the dune surface. The height variation of the sand dune changes the lower boundary of the fluid domain.

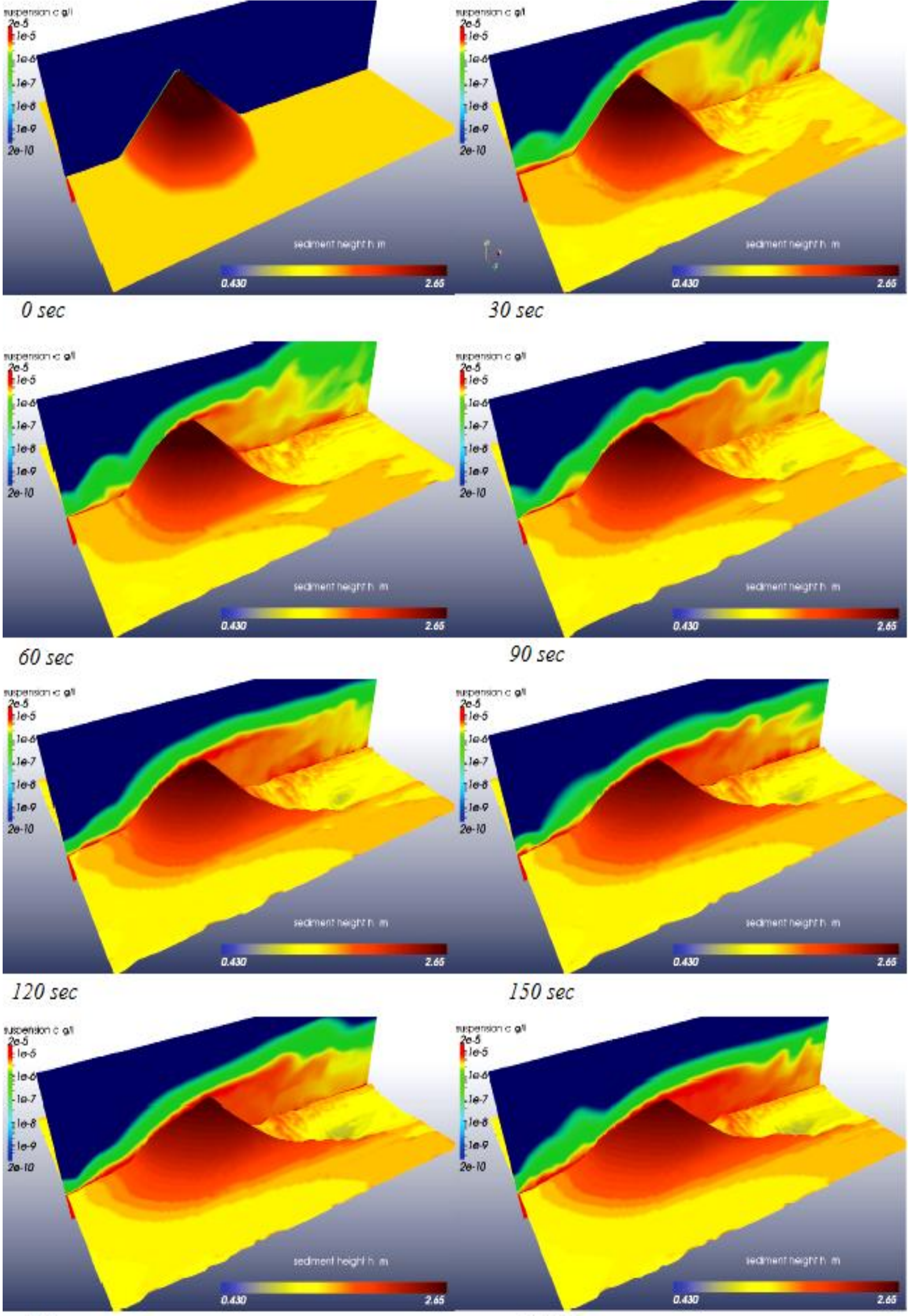
To complete the model, an equation for the sand suspension load is introduced to model the suspension in the fluid body due to advection and diffusion [21]. The sand quantity is given by Eq. (6) which gives the sand mass concentration within the fluid [20]:

$$\frac{\partial c}{\partial t} + \sum_{k=1}^{3} u_k \frac{\partial c}{\partial x_k} + w_g \frac{\partial c}{\partial x_2} - K \sum_{k=1}^{3} \frac{\partial^2 c}{\partial x_k \partial x_k} = 0 \qquad (6)$$

where: c is the mass concentration, K is the diffusion coefficient, w_g an additional velocity for the settling of particles due to gravitation.

The NaSt3DGPF code package comprises both the three dimensional fluid model and the sediment model handling bed load as well as suspension load. The three equations and, implicitly three models used are coupled in each time step calculation. The capability of the full model is illustrated by numerical modelling of the evolution of a barchanoid sand dune from a conic pile of sand initially put in the middle of the flow domain. The coupling of the three equations and implicitly of the three models used takes place at every step of time. An example of the practical efficiency of combining these models is presented by the numerical modelling of the formation of a barchan dune from an initial set of conical sand disposed at the centre of the experimental flow domain. Air is the working fluid for which a parabolic profile is applied as inflow velocity profile. Both types of transport for coarser sand grains and fine particles are taken into account. The following parameters were considered in the numerical simulation: Re=1000, Fr=1 and a grain size of 0.00002 m [18]. The critical angle of repose is modelled according to, by a heuristic approach [16].

Figure 11 illustrates the numerical simulation results of the formation process of a typical crescent shaped barchan dune from the initial pile of sand at various time steps [18]. Figure 12 shows vortex forming around the dune at time step t =210 s. Figure 13 clearly shows the finer sand particles transported by air flow as suspension (t=210 s).



0 sec 30 sec

60 sec 90 sec

120 sec 150 sec

180 sec 210 sec

Fig. 11. Transformation of initial sand pile into a typical crescent-shaped barchan dune [22].

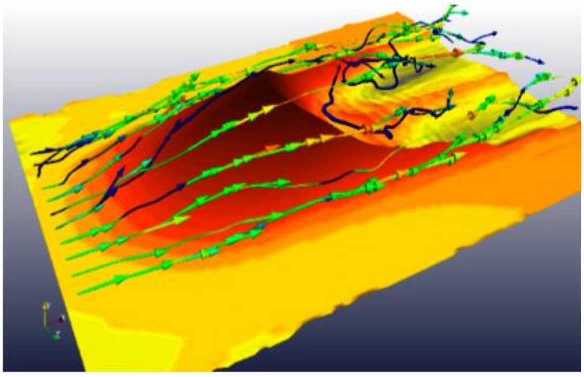


Fig. 12. Vortex forming around the dune [22].

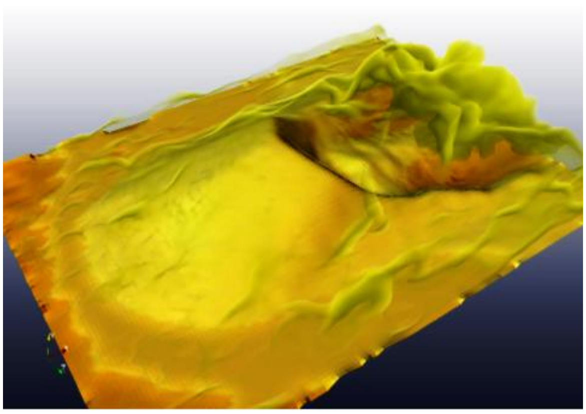


Fig. 13. Transportation of finer sand particles as suspension load [22].

4. PREVENTION OF DESERT EXPANSION AND SAND DUNES FIXATION TECHNIQUES

If 50 years ago desertification was a problem of major importance only in the arid regions of the world, nowadays, more and more countries lose significant agricultural land annually due to soil degradation and desertification. Whereas in the past research was limited only to experiments, with the rapid growth of computer technology, it was replaced by numerical simulation, allowing good prediction of environmental modifications, the experimental tests being used to validate the numerical models.

Keeping under control the sand dune migration can be done by reducing saltation, which can be reduced by soil stabilization, or reducing the wind velocity at ground level. Another sand dune migration control method would be modifying the wind direction to remove and prevent sand deposits. The techniques based on these principles can be divided into two complementary categories: mechanical stabilization and biological setting [23].

4.1. MECHANICAL STABILIZATION OF SAND DUNES

Mechanical stabilization of sand dunes is the used as an initial stage during the sand dune biological crusting. There are more methods of achieving the sand dune mechanical stabilization fixation, the efficiency depending largely on the particularities of the area where being applied. Halting or slowing the movement of sand can be done by protecting fences 1 to 1.5 m high to cause a build-up of sand, leading to the formation of an artificial dune [24]. Protection fences could be of a chess board pattern or fences aimed at preventing sand from advancing. Checkerboard fences are generally built of wooden materials (straws, palm-tree leaves) which can be easily acquired in the vicinity of protected areas and they show a certain permeability to wind.

Fig. 14. Fences in the form of chessboard [24].

The size of rectangular patterns inside the checkerboard largely depends on the land particularities. According to William and Mohammed [23], a typical checkerboard system built in Egypt is 50-70 cm high forming 3 x 3 m rectangles while, according to Guo et al. [25], the typical size for a similar system but for different land conditions is (10-15) cm high forming 1x1m rectangles. The fore dune fences are similar to the vegetation belts except that they are made of palm leaves, wood, fibre glass, concrete, etc. The main purposes of the fore dune fences are either to reduce the wind energy or to divert the direction of the wind from the area that needs to be protected.

Depending on the position of the fence in relation to the dominant wind, we can distinguish between two types of fences: vertical fences which aim to reduce the wind energy and provide sand trapping abilities and diverting fences, slanted at an angle of 120^o to 140^o from the wind direction to divert sand away from the area that needs to be protected (Fig. 15).

Fig. 15. Vertical fence. b) Diverting fence [23].

The mulch or protective screen technique consists of covering the dune uniformly with a natural or artificial screen to prevent saltation. The protection screen can be made of different materials, such as straws, branches, stalks, plastic or acrylic fibres foil and net. Surfaces can also be covered with gravel (Fig. 16), whose granulation and quantity depend on the wind velocity in the protected area (National Cooperative Highway Research Program 1973).

Fig. 16. Stone protective coating used to stabilize sand dunes [27].

In 1950, the Egyptian Desert Institute proved that an area of 1600 ha of desert can be stabilized by water wetting [28]. This brought about an increase in the percentage of the fines (silt and clay) particles between the sand grains, a reduction of the salt content in the soil, which enhanced the growth of more vegetation.

Brines or saline waters rich in carbonate or sulphate salts such as brines can be a good stabilizing agent. With the extended evaporation, the deposition of the salts, present in the brines, tends to cement the sand grains and resist wind erosion [28].

The chemical industry produces a range of chemicals that can be used as stabilizers to control erosion, such as: bitumen, polyelectrolyte, latexes, etc. Chemical stabilizers produce adhesive bonding of the sand granules, forming a film on the sand grains that increases their specific gravity and consequently decrease the rate of erosion [23].

Fig. 17. Sticking of sand particles by chemical stabilizer [27].

5.2. BIOLOGICAL FIXATION OF SAND DUNES

After dunes have been mechanically stabilized, they can then be permanently fixed by planting trees and perennial vegetation (Watson 1985). The choice of species to be planted depends on climatic and ecological conditions. These must be resistant to drought, wind, high temperature variations; they should grow fast and have a high capacity of proliferation (Mohamed et al. 2010).

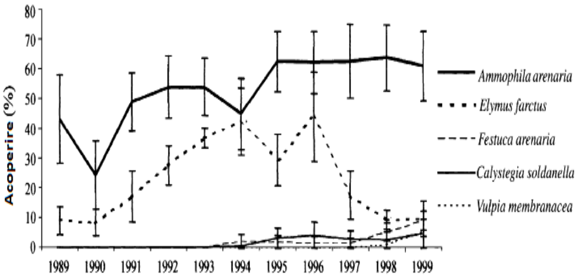


Fig. 18. The dynamics of vegetation on stabilized dunes. Species with smaller contributions than 5% are not shown [32].

The following costs are envisaged for sand dune fixation:

- primary fixation: 0.65 USD / m on fences;
- seedling production: 0.25 USD / plant;
- planting and watering: 0.35 USD / plant;
- security: 15 USD / ha. year.

Assuming an average fence length of 1000 m/ha, a planting density of 200 plants/ha, a rate of 20% of repopulation and ensuring security for 5 years, the average cost would be 850 dollars/ha [32].

5.3. NUMERICAL SIMULATION RESEARCH IN SAND DUNE STABILIZATION AND SETTING

As already stated, numerical simulation is mainly used due to lower costs, faster and more reliable results compared to field studies on large areas of land during long time periods.

To identify the most reliable and cost-effective solution for mechanical dunes stabilization when using checkerboard fences, the size of rectangular patterns should be tailored to local environmental conditions. The size of rectangular patterns within the checkerboard fences can be determined experimentally by building structures of different sizes and studying the effects during long periods of time or by numerical modelling which is much faster and cheaper. Guo et al. [25] used numerical simulation to determine the optimal configuration and size of the checkerboard fences. By using field experiments and simulation with a computational fluid dynamics model was found that a height of (10–20) cm has a substantial effect on dune fixation. The practicable size of the checkerboard of 1m×1m has remarkable wind break and dune fixation effects (Fig. 19).

A numerical simulation was performed to simulate the distribution of wind velocities in the different straw checkerboard sizes using Fluent v.4.5. As in [24] they defined three types of geometry conditions of 20 cm in height and 1m x 1m, 2m x 2m, 3m x 3 m in size. Simulated distribution of wind velocity alone the wind contour in the measuring square was performed for wind velocities of 3, 6 and 9 m/s [24].

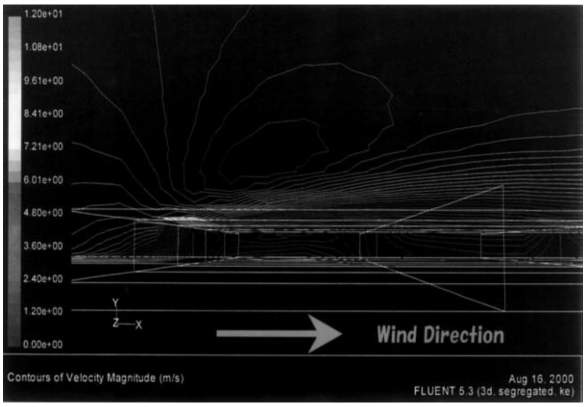


Fig. 19. Simulated distribution of wind velocity alone the wind contour in the measuring square by the CFD model. Wind velocity (e) was set at 10 m/s and the size of the checkerboard at 1m x 1m [25]

The ideal dimensions of the chess board patterned system for the conditions of the land for which the simulation was performed were determined as being made up of squares of 1 m x 1 m. The results numerically achieved were also experimentally confirmed, following the on-field studies [25].

Numerical modelling can be also used to study the growth of vegetation used to stabilize dunes as well as the influence of the increasing plants height on the sand accumulation. Luna et al. [33] used numerical simulation to determine the influence of vegetation development and expansion on coastal sand dune migration in the North-East of Brazil. Figure 20 shows an example of using numerical simulation to estimate coastal sand dune formation depending on the vegetation growth rate.

The numerical simulation results given by the Fluent software were validated based on the experimental field studies [33]. The advantages of using numerical simulation in this field are obvious, significantly reducing the research costs and allowing the performance of an even higher number of simulations, targeting at selecting the most efficient practical solution for the analysed area.

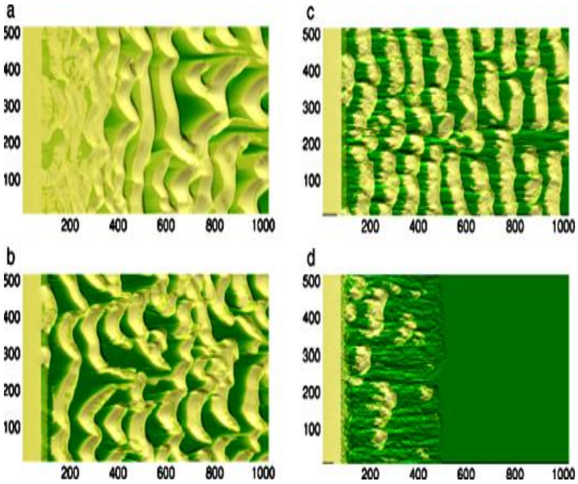


Fig. 20. Coastal sand dunes formation for different vegetation growth rates, V_{υ} (m/year): (a) 2.0; (b) 12.0; (c) 24 and (d) 36, and u = 0.38 m/s [33].

6. CONCLUSIONS

This paper reviews recent developments in the research of sand dune formation, as well as the methods to control desertification. Hence, both experimental and numerical modelling studies are used, as well as field studies during long periods of time.

Sand dunes are analysed according to their shape and structure, then the factors and conditions which concur to their initiation, expansion and migration are described together with stabilization methods and techniques. Field studies conducted in large deserts of the world and wind tunnels experiments are both essential in understanding the processes involved in sand dunes formation, migration and fixing. Field studies and wind tunnels experiments results are validated against the computational predictions obtained by computational fluid dynamics model developed. The comparison between these sets of results reveals good agreement.

Consequently, numerical modelling is a cost-effective, accurate and reliable research method in the study of sand dunes formation according to land particularities and weather conditions.

5. REFERENCES

[1] **Livingstone I, Wiggs F.S.G, Weaver M.C.**, *Geomorphology of desert sand dunes: A review of recent progress*, Earth-Science Reviews, 2007, 80- 3, pp. 239-257.

[2] **Durán O., Parteli E.J.R., Herrmann H.J.**, *A continuous model for sand dunes: Review, new developments and application to barchan dunes and barchan dune fields*, Earth Surf. Process. Landforms, 2010, 35, pp. 1591–1600.

[3]

[4] **Fryberger S.G.,** *Dune forms and wind regime,* In: A Study of Global Sand Seas, Mc Kee ED (Ed.), Geological Survey Professional Paper, U.S. Govt. Printing Office, Washington, 1979, pp. 137–169.

[5] **Kocurek G., Townsley M., Yeh E., Havholm K., Sweet M.L.,** *Dune and dune-field development on Padre Island, Texas, with implications for interdune deposition and water-table-controlled accumulation,* Journal of Sedimentary Research, 1992, 62-4, pp. 622 - 635.

[6] **Wasson R.J., Hyde R.,** *Factors determining desert dunes type,* Nature, 1983, 304, pp. 337–339.

[7] **Zhang Z., Dong Z., Wu G.,** *Field observations of sand transport over the crest of a transverse dune in northwestern China Tengger Desert,* Soil and Tillage Research, 2017, 166, pp. 67–75.

[8] **Yang X., Scuderi L., Liu T., Paillou Ph**., **Hongwei Li., Dong J., Zhu B., Jiang W., Jochems A., Weissmann G.,** *Formation of the highest sand dunes on Earth,* Geomorphology, 2011, 135(1–2), pp. 108-116.

[9] **Hicham E.,** *Initiation and early development of barchans dunes: A case study of the Moroccan Atlantic Sahara Desert,* Geomorphology, 2012, 138. pp. 181–188.

[10] **Hicham E., Douday S.,** *Equilibrium versus disequilibrium of barchan dunes,* Geomorphology, 2011, 125, pp. 558–568.

[11] **Claudin P., Andreotti B.,** *A scaling law for aeolian dunes on Mars, Venus, Earth, and for subaqueous ripples,* Earth and Planetary Science Letters, 2006, 252, pp. 30–44.

[12] **Faria R., Ferreira A.D., Sismeiro J.L., Mendes J.C.F., Sousa A.C.M.,** *Wind tunnel and computational study of the stoss slope effect on the aeolian erosion of transverse sand dunes,* Aeolian Research, 2011, 3, pp. 303–314.

[13] **Ferreira A.D., Oliveira R.A.,** *Wind erosion of sand placed inside a rectangular box,* Journal of *Wind Engineering* and *Industrial Aerodynamics,* 2009, 97, pp. 1–10.

[14] **White B.R.,** *Laboratory simulation of aeolian sand transport and physical modeling of flow around dunes,* Annals of Arid Zone, 1996 35, pp. 187–213.

[15] **Qian G., Dong Z., Luo W., Wang H.,** *Variations of horizontal and vertical velocities over two-dimensional transverse dunes: a wind tunnel simulation of the effect of windward slope,* Journal of Arid Environments, 2009, 73, pp. 1109–1116.

[16] **Parsons D.R., Walker I.J., Wiggs G.F.S**., *Numerical modelling of flow structures over idealized transverse aeolian dunes of varying geometry,* Geomorphology, 2004, 59, pp. 149–164.

[17] **Burkow M., Griebel M.,** *Towards a three-dimensional numerical simulation of fluvial geomorphological processes and the reconstruction of past event,* Zeitschrift für Geomorphologie, 2015, 59, pp. 15-32.

[18] **Adelsberger J., Esser P., Griebel M., Groß S., Klitz M., Rüttgers A.,** *3D incompressible two-phase flow benchmark computations for rising droplets,* Proceedings of the 11th World Congress on Computational Mechanics (WCCM XI), Barcelona, Spain, 2014, pp. 274-5285.

[19] **Smagorinsky J.,** *General circulation experiments with the primitive equations,* Montly Weather Review, 1963, 91, pp. 99–164.

[20] Griebel M., Zaspel P., *A multi-GPU accelerated solver for the three-dimensional two-phase incompressible Navier-Stokes equations,* Computer Science Research and Development, 2010, 25, pp. 65-73.

[21] **Exner F.,** *Uber die Wechselwirkung zwischen Wasser und Geschiebe in Flussen,* Sitzungsbericht Akademie der Wisssenschaft Wien, 134, 1925, pp. 165-180.

[22] **Malcherek A.,** *Sedimenttransport und Morphodynamik. Lecture notes,* Institut fur Wasserwesen, Universitat der Bundeswehr, Munchen, 2004.

[23] **Burkow M.,** *Numerische Simulation strömungsbedingten Sedimenttransports und der entstehenden Gerinnebettformen. Diplomarbeit,* Institut für Numerische Simulation, Universität Bonn, 2010.

[24] **William M. Shehata, Mohammed H. Al-Rehaili,** *A Review on Sand Dune Stabilization,* Saudi Geological Survey, Saudi Arabia, 2013.

[25] **De Boever M., Khlosi M., Delbecque N., De Pue J., Ryken N., Verdoodt A., Cornelis W.M., Gabriels D.,** Desertification and land degradation processes and mitigation, UNESCO Chair of Eremology, Ghent University, Belgium, 2013.

[26] **Guo Yu Qiu, In-Bok Lee, Hideyuki Shimizu, Yong Gao, Guodong Ding**, *Principles of sand dune fixation with straw checkerboard technology and its effects on the environment,* Journal of Arid Environments, 2004, 56, pp. 449–464.

[27] *** US Highway Research Board, *Erosion control on highway construction,* Highway Research Board, National Cooperative Highway Research Program of highway Practice No. 18, 1973.

[28] **Vanoni V.A.,** *Sedimentation Engineering, Manuals and Reports on Engineering Practice,* ASCE, No. 54, 1975.

[29] *** Egyptian Desert Institute, *Sand dunes in Egypt*, (in Arabic), M. Monir (Ed.), Egyptian Desert Institute Publication, 1983.

[30] *** King Fahd University of Petroleum and Minerals (KFUPM), Research Institute, *Laboratory investigation of chemicals for sand stabilization*, Technical Report, Project No. 23046, 1987.

[31] **Watson A.,** *The control of wind-blown sand and moving dunes: a review of the methods of sand control in deserts, with observations from Saudi Arabia*, Quarterly Journal of Engineering Geology & Hydrogeology, 1985, 18, pp. 237-252.

[32] **Mohamed M.O., Saleck M.O., Berte Ch.J.,** *Fighting sand encroachment: lessons from Mauritania*, FAO Forestry paper 158, Roma, 2010.

[33] **Rozé F., Lemauviel S.**, Sand Dune Restoration in North Brittany, France: *A 10-Year Monitoring Study*, Society for Ecological Restoration International, Restoration Ecology, 2004, 12-1, pp. 29-35.

[34] **Luna M.C.M. de M, Parteli E.J.R., Durán O., Herrmann H.J.,** Model for the genesis of coastal dune fields with vegetation. Geomorphology, 2011, 129, pp. 215–224.

Rezumat: Această lucrare analizează stadiul actual al cercetărilor privind formarea dunelor de nisip. Sunt prezentate studii practice privind eroziunea, migrația și formarea dunelor de nisip în deșertul Sahara; studii bazate pe măsurători pe teren. Se prezintă, de asemenea, un studiu experimental privind eroziunea dunelor de nisip realizat în tunelul aerodinamic; un studiu pentru determinarea vitezelor de frecare pe fiecare dintre cele trei modele utilizate. Studiile practice sunt urmate de un studiu de modelare numerică având rezultate suficient de apropiate de rezultatele experimentale pentru a fi validat. Sunt descrise metodele și tehnicile de stabilizare și ancorare a dunelor de nisip, modalitatea de punere în practică a acestora, precum și modul în care modelarea numerică poate fi utilizată în studiul ancorării mecanice și stabilizării biologice a dunelor de nisip.

Cuvinte cheie: modelare numerică, tunel de vânt, dune de nisip, eroziune, migrație.